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Published in:
I E E E Transactions on Communications

DOI (link to publication from Publisher):
10.1109/TCOMM.2012.120512.110669

Publication date:
2013

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Thai, C., Popovski, P., Kaneko, M., & De Carvalho, E. (2013). Multi-flow scheduling for coordinated direct and relayed users in cellular systems. *I E E E Transactions on Communications*, *61*(2), 669 - 678. https://doi.org/10.1109/TCOMM.2012.120512.110669

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Multi-Flow Scheduling for Coordinated Direct and Relayed Users in Cellular Systems

Chan Dai Truyen Thai, Petar Popovski, *Senior Member, IEEE,* Megumi Kaneko, *Member, IEEE,* and Elisabeth de Carvalho, *Member, IEEE*

***Abstract*—There are two basic principles used in wireless network coding to design throughput-efficient schemes: (1) aggregation of communication flows and (2) interference is embraced and subsequently cancelled or mitigated. These principles inspire design of many novel *multi–flow transmission (MFT)* schemes. Such are the Coordinated Direct/Relay (CDR) schemes, where each basic transmission involves two flows to a direct and a relayed user. Usage of MFT schemes as building blocks of more complex transmission schemes essentially changes the problem of scheduling, since some of the flows to be scheduled are coupled in a signal domain and they need to be assigned a communication resource simultaneously. In this paper we define a novel framework that can be used to analyze MFT schemes and assess the system-level gains. The framework is based on cellular wireless users with two-way traffic and it sets the basis for devising composite time-multiplexed MFT schemes, tailored to particular optimization criteria. Those criteria can be formulated by adapting well-known schedulers in order to incorporate MFT schemes. The results show rate advantages brought by the CDR schemes in pertinent scenarios. Another key contribution is the proposed framework, which can be used to evaluate any future multi-flow transmission scheme.**

***Index Terms*—Wireless relay, wireless network coding, interference cancellation, coordinated transmission.**

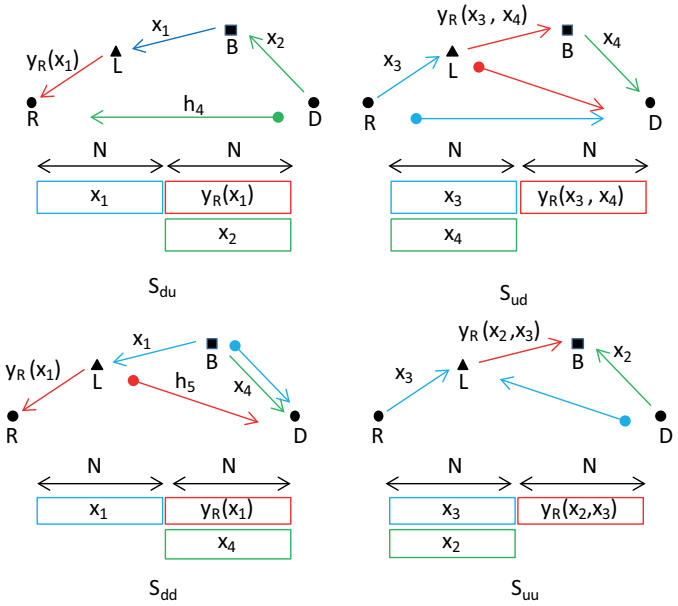


Fig. 1. Individual CDR Schemes S_{du}, S_{ud}, S_{dd} and S_{uu}. In each scheme, the time slot of the transmission represented by an arrow above is also represented by a rectangular below with the same dash style and the transmissions represented by the rectangles in the same column are conducted simultaneously. An interference signal is represented by an arrow with a thick end.

I. Introduction

A. Motivation

WIRELESS network coding has recently emerged as one of the key generic techniques that can boost the throughput performance of wireless networks. A canonical scenario that demonstrates the benefit of wireless Network Coding (NC) is the scenario with Two–Way Relaying (TWR). There are two basic principles used in designing throughput-efficient schemes with wireless network coding:

1) *Aggregation of communication flows.* Instead of transmitting each flow independently, the principle of network coding is used in which flows are sent/processed jointly;
2) *Embracing the interference that can be subsequently cancelled or mitigated.* For example, in analog network coding, flows are allowed to interfere, knowing a priori that the interference can be cancelled by the destination.

Using these two principles can give rise to novel transmission techniques. In [1], [2] we have shown that the communication flows of a direct and a relayed user can be jointly served, which can bring very visible performance benefits with respect to the reference (conventional) way of serving the same communication flows. The four schemes discussed in [2] are described on Fig. 1. Assume for example that a direct user wants to send a packet to Base Station (BS) B, while the BS has a packet to send to a relayed user. In a conventional cellular system, these packets are sent over separate UL/DL phases. Instead, as seen in scheme S_{du} of Fig. 1 the BS may first send the packet which is received at Relay Station (RS) L. While the RS forwards this packet to its intended relayed user, the direct user sends its packet to the BS, thus saving the required transmission time compared to the conventional method. We term such a scheme *coordinated direct/relay (CDR)* transmission scheme.

Despite the fact that each individual scheme from [2] brings throughput benefit with respect to the related reference schemes, the system-level aspects of these novel transmission

Paper approved by X. Zhang, the Editor for Wireless Networks and Techniques of the IEEE Communications Society. Manuscript received October 5, 2011; revised July 18, 2012.

This work is supported by the Danish Research Council for Technology and Production, grant nr. 09 – 065035, and by the Grant-in-Aid for Scientific Research no. 10595739 from the Ministry of Education, Science, Sports and Culture of Japan.

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Digital Object Identifier 10.1109/TCOMM.2012.120512.110669

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schemes remain largely unclear. In [2] there was a preliminary study on how the individual CDR schemes can be used as building blocks for scheduling schemes to serve multiple users. However, the multi–user scenario in [2] is rather limited and cannot provide satisfactory answers in comparing the CDR schemes with other state-of-the-art schemes, notably the two-way relaying [3].

One of the main objectives of this paper is to define a suitable framework for analyzing and comparing the *multi–flow transmission (MFT) schemes*, such as CDR and two–way relaying. Rigorously speaking, any time–division scheme in which e.g. the communication flows of multiple users are served in the downlink, is a MFT scheme. However, here we use the term MFT scheme to denote a transmission scheme in which the multiple flows are essentially coupled in the signal domain, they use the wireless medium simultaneously, and cannot be decoupled via time division. This is true, for example, for a two–way relaying scheme with wireless network coding based on amplify–and–forward [4]. That is an MFT scheme and the signal–domain coupling is seen in the fact that the achievable rate region is not the triangle obtained by time–division between two one–way relaying schemes.

In attempting to define the suitable analytical framework, we need to change the scheduling task from its usual definition ("at a given time, allocate the single communication resource to a certain communication flow ") to a definition that can deal with MFT schemes ("at a given time, allocate the single communication resource to a group of communication flows"). With such prerequisites, the problem at hand can be defined as follows. Suppose that M flows should be served in a given scheduling epoch. In that case the performance of any proposed algorithm to serve these flows can be assessed by an $M-$dimensional achievable rate region. The central question that we will address is: how much can we enlarge the region of achievable rates if the algorithm that serves the flows can leverage on MFT schemes? In particular, we investigate the benefits of applying the CDR schemes.

The work in this paper treats the case in which any relaying operation is conducted by using amplify–and–forward. Using other relaying techniques may change the analysis and the conclusions, but, the analysis framework and the problem at hand, sublimed in the central question above, remains the same. This framework consists of scenarios and methods for combining MFT schemes into a single composite scheme that serves multiple flows. Another contribution is that we apply insights from practice in order to put constraints on the communication flows and restrict the analysis of the achievable rate regions to tractable, two-dimensional sub-regions. Finally, we consider multi–user scenarios for which we show how several canonical schedulers (Round Robin, Maximum Sum–Rate (Opportunistic Scheduler), Proportional Fair scheduler) can be formulated and applied when MFT schemes are used as building blocks for transmission.

Surveying the related work and regarding the combination of the transmissions of two users, transmission schemes that are somewhat related to the schemes treated in this paper have appeared before [5], [6], or to relayed users [7], [8]. In another aspect, regarding the joint resource allocation of uplink and downlink of a user, [9], [10] and references therein discuss that the total amount of resource for uplink and downlink can be dynamically adjusted and the uplink and downlink satisfy the user as in a common service. In this paper, we jointly allocate uplink/downlink resources to different user types and analyze the rate performance under different scheduling policies. On the other hand, several advanced versions of TWR NC have been proposed e.g. the optimization of the different phase durations in TWR NC is considered in [12] and the space distribution of users is exploited to optimize the TWR NC scheme in [11]. Therefore in this paper, we treat TWR NC as a building block that represents the state-of-the-art.

The paper is organized as follows. Section II presents the network model of the paper. We present the individual schemes in section III. Section IV describes the composite schemes and presents the framework for analyzing the achievable rate region. Section V compares the reference schemes and CDR schemes using different schedulers while Section VI presents and analyzes the numerical results. Section VII concludes the paper.

II. System Model

We first introduce the relevant notation and system concepts by considering a cellular network with one base station (B), one relay (L), one relayed user (R) and one direct user (D) see Fig. 1. The direct channel BS-R is assumed weak and R relies only on the amplified/forwarded signal from the RS in order to decode the signal from the BS. All transmissions are in one frequency with a normalized bandwidth of 1 Hz. All stations are single-antenna and half-duplexed. Each of the complex channels h_{ij}, $i,j \in \{B,L,R,D\}$, is reciprocal, known at the receiver. We assume all the channels are known at the BS as in [14], [15]. Each user requests an uplink and a downlink transmissions to the BS. We assume that the data to/from each user is *infinitely backlogged* so that there are always data to transmit as in many works regarding downlink [16] and Two-way Relaying optimization [17] and scheduling [18], [19]. Thus the achievable rate for a user at a certain time is equal to the information theoretic capacity, i.e. $\mathrm{C}(\gamma) = \log_2(1+\gamma)$, where γ denotes an instantaneous received signal-to-noise ratio (SNR) of the channel used. Therefore the maximal rate received at a station over channel l is $\mathrm{C}(\gamma_l)$.

We use the following notation, with a slight abuse: x_i may denote a packet or a single symbol, and it will be clear from the context. For example, the packet that the BS wants to send to user R is denoted by x_1; but if we want to express the signal received, then we use expressions of type $y = hx_1 + z$, where y, x_1 and z_1 denote symbols (received, sent and noise respectively). We introduce further notations: x_4 is the packet sent from the BS to D, while the packets that the BS needs to receive are x_3 from user R and x_2 from D. x_1, x_2, x_3 and x_4 are therefore corresponding to 4 traffic types: relayed downlink (Rd), direct uplink (Du), relayed uplink (Ru) and direct downlink (Dd) respectively. Throughout this paper, small u and d denote uplink and downlink while capitalized D and R denote the direct and relayed users respectively. All relaying transmissions in this paper are Amplify-and-Forward (AF).

The transmissions are organized in *scheduling epochs* with fixed duration. The channels are constant throughout the

scheduling epoch. In this paper we will assume that in each epoch two users will be served, each having uplink/downlink traffic, which corresponds to four flows per epoch. If there are more than two users in the system, then two of them are selected according to a certain scheduling criterion and, again only four flows are served in an epoch. During a scheduling epoch several different transmission schemes can be multiplexed in time, including both MFT schemes and single–flow transmission (SFT) schemes. The part of the epoch during which a fixed transmission scheme is used is termed *frame*. While the duration of a scheduling epoch is fixed, the duration of each frame within the scheduling epoch is variable and subject to optimization. The transmission schemes corresponding to different frames will be introduced in the next section.

In an individual scheme, the received signal and Additive White Gaussian Noise (AWGN) at the BS, the RS, user R and user D in time slot j is denoted by $y_i[j]$ and $z_i[j] \sim \mathcal{CN}(0,\sigma^2),\ i \in \{B,L,R,D\},\ j \in \{1,2\}$. The average transmit power at all stations is 1, $\mathrm{E}[|s|^2]=1$, s is a symbol when transmission is done at the BS, user R or D, s is a relayed signal when transmission is done at the RS. At the RS, the received signal is scaled to comply with transmit constraint.

Regarding the notation, for a compact notation, we will write the matrices by using ";" to separate different rows of a matrix. For example, the $2\times n$ matrix with $1\times n$ row vectors $\mathbf{a}_1, \mathbf{a}_2$ can be written as $[\mathbf{a}_1;\mathbf{a}_2]$ instead of $\begin{bmatrix}\mathbf{a}_1\\ \mathbf{a}_2\end{bmatrix}$.

III. Transmission Schemes: The Building Blocks

In this section we introduce the transmission schemes, where each scheme is a candidate to be used during a frame that is a part of a certain scheduling epoch. The candidate schemes are of two types, SFT schemes and MFT schemes. We first describe the four MFT schemes based on coordinated direct and relay (CDR) transmission. The other schemes that can be used in a frame feature conventional one–way direct and relayed transmission, as well as the two–way relaying. It should be noted that different transmission schemes correspond to different set of communication flows. For example, the first scheme, denoted S_{du} on Fig. 1 serves two flows, the BS to user R and user D to the BS, respectively. Another scheme would be an SFT scheme in which only the flow user D to the BS is served - hence, the set of flows in this latter case is a subset, but not identical to the set of flows used in S_{du}.

A. Multi–Flow Transmission Schemes with CDR

Each of schemes S_{du}, S_{ud}, S_{dd}, S_{uu} combines two communication flows, one associated with a direct and another with a relayed user, respectively. There are four possible flows associated with these two users, which we have already denoted as Dd, Du, Rd, Ru. Each of the four schemes is an MFT scheme that has a duration of $2N$ symbols. S_{du} combines Du and Rd, subscript du means that the relayed user (the first user) has a downlink message and the direct user (the second user) has an uplink message. S_{ud} combines Dd and Ru, S_{dd} combines Dd and Rd and S_{uu} combines Du and Ru. The time interval of $2N$ used by a given scheme is divided into two time *slots*, each having N symbols. In each slot, one single transmission or two simultaneous transmissions are performed. The transmissions in each scheme are arranged so that the interference is reduced or cancelled. We present each scheme in details below.

1) Coordinated Scheme S_{du}: BS transmits x_1 to the RS in the first slot, the RS receives $y_L[1]=h_{BL}x_1+z_L[1]$ (Fig. 1). In the second slot, the RS scales the received signal with the amplification factor $\alpha_{S_{\mathrm{du}}}=\frac{1}{|h_{BL}|^2+\sigma^2}$ and transmits it. At the same time, D transmits x_2. User R therefore receives signal $y_R[2]=h_{LR}\sqrt{\alpha_{S_{\mathrm{du}}}}y_L[1]+h_{RD}x_2+z_R[2]=h_{LR}\sqrt{\alpha_{S_{\mathrm{du}}}}h_{BL}x_1+h_{LR}\sqrt{\alpha_{S_{\mathrm{du}}}}z_L[1]+h_{RD}x_2+z_R[2]$ and the BS receives $y_B[2]=h_{BL}\sqrt{\alpha_{S_{\mathrm{du}}}}y_L[1]+h_{BD}x_2+z_B[2]=h_{BL}\sqrt{\alpha_{S_{\mathrm{du}}}}h_{BL}x_1+h_{BL}\sqrt{\alpha_{S_{\mathrm{du}}}}z_L[1]+h_{BD}x_2+z_B[2]$. Since the BS *knows* x_1 and all channels, it cancels the component in x_1 in $y_B[2]$, gets $\tilde{y}_B[2]=h_{BD}x_2+h_{BL}\sqrt{\alpha_{S_{\mathrm{du}}}}z_L[1]+z_B[2]$ and decodes x_2 with SNR $\gamma_D^{S_{\mathrm{du}}}=\frac{|h_{BD}|^2}{|h_{BL}|^2\alpha_{S_{\mathrm{du}}}\sigma^2+\sigma^2}=\frac{|h_{BD}|^2(|h_{BL}|^2+\sigma^2)}{2|h_{BL}|^2\sigma^2+\sigma^4}=\frac{\gamma_{BD}(\gamma_{BL}+1)}{2\gamma_{BL}+1}$. User R decodes x_1 treating x_2 as Gaussian noise with SINR $\gamma_R^{S_{\mathrm{du}}}=\frac{|h_{LR}|^2\alpha_{S_{\mathrm{du}}}|h_{BL}|^2}{|h_{LR}|^2\alpha_{S_{\mathrm{du}}}\sigma^2+|h_{RD}|^2+\sigma^2}=\frac{\gamma_{BL}\gamma_{LR}}{\gamma_{BL}+\gamma_{LR}+\gamma_{RD}+\gamma_{BL}\gamma_{RD}+1}$. We have the corresponding rates $R_D^{S_{\mathrm{du}}}=\frac{1}{2}\mathrm{C}\left(\gamma_D^{S_{\mathrm{du}}}\right)$ and $R_R^{S_{\mathrm{du}}}=\frac{1}{2}\mathrm{C}\left(\gamma_R^{S_{\mathrm{du}}}\right)$.

2) Coordinated Scheme S_{ud}: User R transmits x_3 and the BS transmits x_4 simultaneously in the first slot (Fig. 1). The RS receives $y_L[1]=h_{LR}x_3+h_{BL}x_4+z_L[1]$ and D receives $y_D[1]=h_{RD}x_3+h_{BD}x_4+z_D[1]$. In the second slot, RS scales the received signal with the amplification factor $\alpha_{S_{\mathrm{ud}}}=\frac{1}{|h_{BL}|^2+|h_{LR}|^2+\sigma^2}$ and transmits it. The BS receives $y_B[2]=h_{BL}\sqrt{\alpha_{S_{\mathrm{ud}}}}y_L[1]+z_B[2]$ and user D receives $y_D[2]=h_{LD}\sqrt{\alpha_{S_{\mathrm{ud}}}}y_L[1]+z_D[2]$. Since the BS *knows* x_4 and the channels, it cancels x_4 component in y_B, gets $\tilde{y}_B[2]=h_{BL}\sqrt{\alpha_{S_{\mathrm{ud}}}}(h_{LR}x_3+z_L[1])+z_B[2]$ and decodes x_3. At D, $y_D[1]$ and $y_D[2]$ form a virtual 2-antenna received signal $\mathbf{y}=\mathbf{H}\mathbf{x}+\mathbf{z}$, with $\mathbf{y}=[y_D[1]\ y_D[2]]^T, \mathbf{x}=[x_4\ x_3]^T, \mathbf{z}=[z_D[1],\ h_{LD}\sqrt{\alpha_{S_{\mathrm{ud}}}}z_L[1]+z_D[2]]^T$, and

$$\mathbf{H}=\begin{bmatrix} h_{BD} & h_{RD}\\ \sqrt{\alpha_{S_{\mathrm{ud}}}}h_{BL}h_{LD} & \sqrt{\alpha_{S_{\mathrm{ud}}}}h_{LR}h_{LD}\end{bmatrix}. \quad (1)$$

We can apply the MMSE receiver as in [20] to have the rates $R_R^{S_{\mathrm{du}}}=\frac{1}{2}\mathrm{C}\left(\frac{\gamma_{BL}\gamma_{LR}}{2\gamma_{BL}+\gamma_{LR}+1}\right)$ and $R_D^{S_{\mathrm{du}}}=\frac{1}{2}\mathrm{C}\left[\frac{\gamma_{BD}(\gamma_{BL}+\gamma_{LR}+\gamma_{LD}+1)+\gamma_{LD}(\gamma_{BL}+\gamma_{b2})}{(\gamma_{RD}+1)(\gamma_{BL}+\gamma_{LR}+\gamma_{LD}+1)+\gamma_{LR}\gamma_{LD}}\right]$.

3) Coordinated Scheme S_{dd}: BS transmits x_1 in the first slot, the RS relays it to user R and the BS transmits x_4 simultaneously in the second slot (Fig. 1). The transmissions are $y_L[1]=h_{BL}x_1+z_L[1],\ \alpha_{S_{\mathrm{dd}}}=\frac{1}{|h_{BL}|^2+\sigma^2},\ y_R[2]=h_{LR}\sqrt{\alpha_{S_{\mathrm{dd}}}}y_L[1]+z_R[2],\ y_D[1]=h_{BD}x_1+z_D[1],\ y_D[2]=h_{LD}\sqrt{\alpha_{S_{\mathrm{dd}}}}y_L[1]+h_{BD}x_4+z_D[2]$. User R decodes x_1 from $y_R[2]$ without interference. At D, $y_D[1]$ and $y_D[2]$ form a virtual 2-antenna received signal $\mathbf{y}=\mathbf{H}\mathbf{x}+\mathbf{z}$, with $\mathbf{y}=[y_D[1]\ y_D[2]]^T, \mathbf{x}=[x_4\ x_1]^T, \mathbf{z}=[z_D[1]\ h_{LD}\sqrt{\alpha_{S_{\mathrm{dd}}}}z_L[1]+z_D[2]]^T$, and $\mathbf{H}=\begin{bmatrix}0 & h_{BD}\\ h_{BD} & \sqrt{\alpha_{S_{\mathrm{dd}}}}h_{BL}h_{LD}\end{bmatrix}$. We can apply the MMSE receiver to have the rates $R_R^{S_{\mathrm{du}}}=$

$\frac{1}{2}\mathrm{C}\left(\frac{\gamma_{BL}\gamma_{LR}}{\gamma_{BL}+\gamma_{LR}+1}\right)$ and

$$R_D^{S_{\mathrm{du}}} = \frac{1}{2}\mathrm{C}\left[\frac{\gamma_{BD}(\gamma_{BD}+1)(\gamma_{BL}+1)}{(\gamma_{BL}+\gamma_{LD}+1)(\gamma_{BD}+1)+\gamma_{BL}\gamma_{LD}}\right]. \quad (2)$$

4) Coordinated Scheme S_{uu}: User R transmits x_3 and user D transmits x_2 in the first slot. In the second slot, the RS transmits what it received in the first slot (Fig. 1). The transmissions are $y_L[1] = h_{LR}x_3 + h_{LD}x_2 + z_L[1]$, $\alpha_{S_{\mathrm{uu}}} = \frac{1}{|h_{LR}|^2+|h_{LD}|^2+\sigma^2}$, $y_B[1] = h_{BD}x_2 + z_B[1]$, $y_B[2] = h_{BL}\sqrt{\alpha_{S_{\mathrm{uu}}}}y_L[1] + z_B[2]$. The BS decodes x_2 and x_3 from $y_B[1]$ and $y_B[2]$. Similar to the previous schemes, we have $\mathbf{y} = \mathbf{H}\mathbf{x}+\mathbf{z}$, with $\mathbf{y} = [y_B[1]\ y_B[2]]^T, \mathbf{x} = [x_2\ x_3]^T, \mathbf{z} = [z_B[1]\ h_{BL}\sqrt{\alpha_{S_{\mathrm{uu}}}}z_L[1] + z_B[2]]^T$, and $\mathbf{H} = \begin{bmatrix} h_{BD} & 0 \\ \sqrt{\alpha_{S_{\mathrm{uu}}}}h_{BL}h_{LD} & \sqrt{\alpha_{S_{\mathrm{uu}}}}h_{BL}h_{LR} \end{bmatrix}$. We can apply MMSE receiver for both users to have the sum–rate. We have the rates $R_R^{S_{\mathrm{du}}} = \frac{1}{2}\mathrm{C}\left[\frac{\gamma_{BL}\gamma_{LR}(\gamma_{BD}+1)}{\gamma_{BL}\gamma_{LD}+(\gamma_{BL}+\gamma_{LR}+\gamma_{LD}+1)(\gamma_{BD}+1)}\right]$ and $R_D^{S_{\mathrm{du}}} = \frac{1}{2}\mathrm{C}\left[\gamma_{BD} + \frac{\gamma_{BL}\gamma_{LD}}{\gamma_{BL}+\gamma_{LR}+\gamma_{LD}+\gamma_{BL}\gamma_{LR}+1}\right]$.

B. Reference Transmission Schemes

In this part we describe other transmission schemes that can be used to build a composite reference scheme. The motivation comes from the following: If a designer is not aware about the CDR schemes receives the task to serve M communication flows in a given epoch, which schemes are at his/her disposal? Clearly, the first candidates are the usual single–flow schemes, which we, for convenience, denote as S_{od}, S_{ou}, S_{do} and S_{uo}. Scheme S_{od} is a one-hop transmission from the BS to user D (Fig. 2). The BS transmits x_4 (Dd) and user D receives $y_D = h_{BD}x_4 + z_D$ and decodes x_4 with the maximal achievable rate of $R_D^{S_{\mathrm{od}}} = \mathrm{C}(\gamma_{BD})$. In scheme S_{ou}, user D transmits x_2 (Du) and the BS receives. Similarly, we have the same maximal achievable rate of $R_D^{S_{\mathrm{ou}}} = \mathrm{C}(\gamma_{BD})$. In scheme S_{do}, first the BS transmits x_1 (Rd), the RS receives $y_L = h_{BL}x_1 + z_L$, amplifies with amplification factor $\alpha_{S_{\mathrm{do}}} = \frac{1}{|h_{BL}|^2+\sigma^2}$ and transmits. User R receives and decodes x_1 with the maximal achievable rate of $R_R^{S_{\mathrm{do}}} = \mathrm{C}\left(\frac{\gamma_{BL}\gamma_{LR}}{\gamma_{BL}+\gamma_{LR}+1}\right)$. The transmission in the opposite direction (Ru) is conducted in scheme S_{uo}. We have the same maximal achievable rate $R_R^{S_{\mathrm{uo}}} = R_R^{S_{\mathrm{do}}}$.

As a part of the reference transmission schemes, we consider the *TWR NC* based on AF. In accordance with the other schemes, this will be denoted S_{TWR} and it consists of the transmission from the BS to user R (Rd) and the transmission from user R to the BS (Ru) using TWR NC (Fig. 2). First, in the Multiple Access phase, the BS and user R simultaneously transmit x_1 (Rd) and x_3 (Ru) respectively in N symbols, the RS receives $y_L = h_{BL}x_1 + h_{LR}x_3 + z_L$, amplifies it with amplification factor $\alpha_{S_{\mathrm{TWR}}} = \frac{1}{|h_{BL}|^2+|h_{LR}|^2+\sigma^2}$ and transmits it in the Broadcast phase in N symbols. User R receives, cancels the contribution of x_3 and decodes x_1 with SINR $\gamma_{\mathrm{d}}^{S_{\mathrm{TWR}}} = \frac{\gamma_{BL}\gamma_{LR}}{\gamma_{BL}+2\gamma_{LR}+1}$. The BS receives, cancels the contribution of x_1 and decodes x_3 with SINR $\gamma_{\mathrm{u}}^{S_{\mathrm{TWR}}} = \frac{\gamma_{BL}\gamma_{LR}}{2\gamma_{BL}+\gamma_{LR}+1}$. We have the rates corresponding to the relayed uplink and downlink $R_u^{S_{\mathrm{TWR}}} = \frac{N\mathrm{C}\left(\gamma_u^{S_{\mathrm{TWR}}}\right)}{2N} = \frac{1}{2}\mathrm{C}\left(\gamma_u^{S_{\mathrm{TWR}}}\right)$ and $R_d^{S_{\mathrm{TWR}}} = \frac{1}{2}\mathrm{C}\left(\gamma_d^{S_{\mathrm{TWR}}}\right)$.

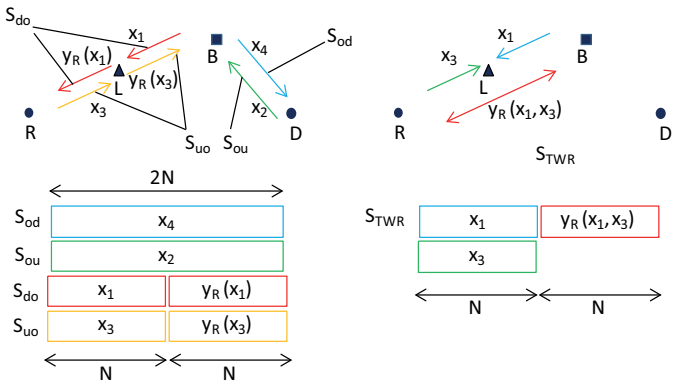


Fig. 2. Individual schemes S_{od}, S_{ou}, S_{do}, S_{uo} and S_{TWR}.

IV. Multi-Flow Framework for Analyzing the Achievable Rate Region

A. Composite Transmission Scheme with Time Multiplexing

Having introduced the individual transmission schemes, we now discuss the key element of the framework for analyzing the system–level performance improvements brought by the CDR schemes. The same reasoning can be used for any other proposal of a multi–flow transmission scheme. The first assumption is that each user has two–way traffic and both flows are backlogged with packets. The scheduling task is now defined as follows. *In a given scheduling epoch, one direct and one relayed user are served, each with two way traffic. Determine how to multiplex the nine transmission schemes in time within the epoch in order to serve the users by optimizing a certain criterion.* The concrete criterion can vary, e. g. optimize the sum rate under the constraint of equal rates between the direct and the relayed user, etc. We will discuss such criteria in the upcoming sections. Note that this framework represents a meaningful, but non-obvious way to compare the proposed schemes since e. g. direct comparison between S_{ud} and S_{TWR} does not make sense.

The reader might object that this definition of the scheduling task is restrictive, as it uses the constraint that, in a scheduling epoch, we select one relayed and one direct user, but not e. g. two relayed users. Indeed, this definition is tailored to the structure of the proposed CDR schemes and fits our needs to investigate the gains brought by these schemes over the reference schemes $S_{\mathrm{od}}, S_{\mathrm{ou}}, S_{\mathrm{do}}, S_{\mathrm{uo}}, S_{\mathrm{TWR}}$. If we allow to schedule two relayed users in a given epoch, then these users would be served by time multiplexing of the schemes $S_{\mathrm{do}}, S_{\mathrm{uo}}, S_{\mathrm{TWR}}$, without involving the CDR schemes. Clearly, one can propose a MFT scheme in which the flows of two different relayed users are coupled, similar to the CDR schemes. However, such schemes are outside the scope of this work. On the other hand, the approach that we present here can be easily extended to analyze any new scheme that couples two or more flows of two or more relayed/direct users or any combination of them.

More formally, in a given epoch of duration T the individual scheme S_i, S_i, $i \in \{\mathrm{du}, \mathrm{ud}, ..., \mathrm{TWR}\}$, occupies a frame of duration $\theta_i T$, where the sum of fractions satisfies $\sum_{i=1}^{9}\theta_i = 1$ as shown in Fig. 3. The performance of the composite scheme is described by a four-dimensional rate

$$\mathbf{A} = \{A_{ij}\} = \overset{\text{scheme number}\ \rightarrow}{\begin{pmatrix} 0 & R_D^{S_{\rm ud}} & R_D^{S_{\rm dd}} & 0 & R_D^{S_{\rm od}} & 0 & 0 & 0 & 0 \\ R_D^{S_{\rm du}} & 0 & 0 & R_D^{S_{\rm uu}} & 0 & R_D^{S_{\rm ou}} & 0 & 0 & 0 \\ R_R^{S_{\rm du}} & 0 & R_R^{S_{\rm dd}} & 0 & 0 & 0 & R_R^{S_{\rm do}} & 0 & R_{\rm d}^{S_{\rm TWR}} \\ 0 & R_R^{S_{\rm ud}} & 0 & R_R^{S_{\rm uu}} & 0 & 0 & 0 & R_R^{S_{\rm uo}} & R_{\rm u}^{S_{\rm TWR}} \end{pmatrix}} \Bigg\downarrow \text{ flow number} \tag{3}$$

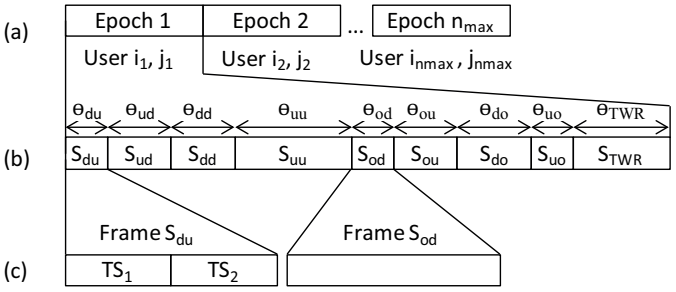


Fig. 3. (a) The transmissions are organized as in epochs with the same durations, (b) An example of an epoch conducted in $S_{\rm all}$, (c) Examples of two-slot frame of $S_{\rm du}$ and one-slot frame of $S_{\rm od}$.

vector $\mathbf{r} = [R_{Dd}\ R_{Du}\ R_{Rd}\ R_{Ru}]^T = [R_1\ R_2\ R_3\ R_4]^T$, corresponding to the four communication flows Dd, Du, Rd, and Ru, respectively. We will use the notation R_1 and R_{Dd} interchangeably, also for the other three flows. The total rate achieved by a given flow in the scheduling epoch consists of contributions from each of the individual schemes that serves that flow, e.g. R_{Du} has contributions from $S_{\rm du}, S_{\rm uu}, S_{\rm ou}$. For a compact representation, denote $\mathbf{A}$ as in (3) in which the element at row i and column j is the rate contribution from the individual scheme $S_j,\ j \in \{$du, ud, dd, uu, od, ou, do, uo, TWR$\}$ which is equivalent to column 1, 2, ..., 9 respectively, to the $i-$th flow ($R_i,\ i \in \{1, ..., 4\}$). Hence, the four-dimensional region of the rates that can be achieved by the composite scheme is described as $\mathbf{0}_4 \preceq \mathbf{r} \preceq \mathbf{A}\boldsymbol{\theta}$ where $\mathbf{0}_p$ or $\mathbf{1}_p$ is the column vector $[0, ..., 0]^T$ or $[1, ..., 1]^T$ with p elements. The operator $\preceq$ implies that for each vector component $\leq$ is satisfied. The region is obtained by varying $\boldsymbol{\theta}$ such that $\mathbf{0}_9 \preceq \boldsymbol{\theta} \preceq \mathbf{1}_9$ and $\mathbf{1}_9^T \cdot \boldsymbol{\theta} = 1$.

The reference combined scheme $S_{\rm ref}$ consisting of only reference individual schemes is a special case of $S_{\rm all}$ when $\theta_{\rm du} = \theta_{\rm ud} = \theta_{\rm dd} = \theta_{\rm uu}$. Similarly, we have CDR composite schemes $S_{\rm duud}$ when all $\theta_i = 0$ except $\theta_{\rm du}$, $\theta_{\rm ud}$ and $S_{\rm dduu}$ when all $\theta_i = 0$ except $\theta_{\rm dd}$, $\theta_{\rm uu}$. While $S_{\rm all}$ is the multiplexing of all defined reference and CDR schemes, $S_{\rm CDR}$ is the multiplexing of all CDR schemes and $S_{\rm ref}$ is the multiplexing of all reference schemes. In the following parts, we will analyze and compare these composite schemes; the gain by the CDR schemes is seen in the enlarged rate region offered by $S_{\rm all}$ compared to $S_{\rm ref}$.

B. Rate Analysis with Uplink/Downlink Coefficient

A comprehensive analysis of the achievable rate region for the composite transmission scheme involves consideration of four–dimensional regions, which is not always tractable or sufficiently informative. In order to collapse the rate region to subregions of practical interest, we resort to the features of the communication flows served in an epoch. By assumption, each of the users (direct or relayed) scheduled in an epoch, has both uplink and downlink traffic. In a conventional approach, the uplink demand and downlink demand of a user in a wireless network consisting of a base station (or an access-point) and multiple users (mobiles) are independently allocated in different resource portions (TDD, FDD or CDMA). This happens *despite* the fact that the uplink and the downlink traffic of a given user can exhibit dependence that emerges from e.g. the application–layer behavior and needs. For example, the downlink/uplink ratio is often fixed and depends on the type of application e. g. gaming and calls have ratio of 1:1, web browsing has a ratio of about 5:1 [13]. Generally, we can assume that the downlink rate demand and the uplink rate demand of a user satisfies, as in [10], $R_{i,d} = \beta_i R_{i,u},\ i \in \{R, D\}$, where β_i is termed *uplink/downlink ratio (UDC)* for the $i-$th user.

We assume that the traffic demands by the $i-$th user are posed by specifying the UDC, defined as follows. In a certain scheduling epoch, all uplink/downlink flows of users are served and the rates are selected such that UDC is achieved for each of the served users. More formally, let $(R_{D,i}(n), R_{R,i}(n))$ be the downlink/uplink rates achieved for the $i-$th user in $n-$th scheduling epoch. Then with any n, $\frac{R_{d,i}(n)}{R_{u,i}(n)} = \beta_i$.

In the following we analyze the rate region under the UDC constraints for the composite scheme $S_{\rm all}$, let us represent the matrix $\mathbf{A}$ as $\mathbf{A} = \left[\ \mathbf{a}_1^T; \mathbf{a}_2^T; \mathbf{a}_3^T; \mathbf{a}_4^T\ \right]$ where e.g. $\mathbf{a}_p^T$ is the p-th row of $\mathbf{A}$ in (3). We are now interested in getting the bound for the two-dimensional vector that contains only the downlink rates $\mathbf{r}_d = [R_{Dd}\ R_{Rd}]^T$. Let the corresponding vector of uplink rates be $\mathbf{r}_u = [R_{Du}\ R_{Ru}]^T$, such that $\mathbf{r}_d = \begin{bmatrix} \beta_D & 0 \\ 0 & \beta_R \end{bmatrix} \mathbf{r}_u$.

Considering the direct user, if $\mathbf{a}_1^T\boldsymbol{\theta} \leq \beta_D \mathbf{a}_2^T\boldsymbol{\theta}$, we select $R_{Dd} = \mathbf{a}_1^T\boldsymbol{\theta}$ and $R_{Du} = \frac{\mathbf{a}_1^T\boldsymbol{\theta}}{\beta_D}$. If $\mathbf{a}_1^T\boldsymbol{\theta} > \beta_D \mathbf{a}_2^T\boldsymbol{\theta}$, we select $R_{Dd} = \beta_D \mathbf{a}_2^T\boldsymbol{\theta}$ and $R_{Du} = \mathbf{a}_2^T\boldsymbol{\theta}$. Thus $R_{Dd} = \min\left\{\mathbf{a}_1^T\boldsymbol{\theta}, \beta_D \mathbf{a}_2^T\boldsymbol{\theta}\right\}$. R_{Rd} is derived similarly. Now the two dimensional region is determined by:

$$0 \preceq \mathbf{r}_d \preceq \left[\min\left\{\mathbf{a}_1^T\boldsymbol{\theta}, \beta_D \mathbf{a}_2^T\boldsymbol{\theta}\right\}, \min\left\{\mathbf{a}_3^T\boldsymbol{\theta}, \beta_R \mathbf{a}_4^T\boldsymbol{\theta}\right\}\right]^T. \tag{4}$$

To see how the rate region looks like we consider the simple case of $S_{\rm duud}$. In this case, $\theta_{\rm dd} = \theta_{\rm uu} = ... = \theta_{\rm TWR} = 0$ and $\theta_{\rm ud} = 1 - \theta_{\rm du}$. Replacing $\boldsymbol{\theta}$ with $[\theta_{\rm du}, 1 - \theta_{\rm du}, 0, 0, 0, 0, 0, 0, 0]^T$ and $\mathbf{A}$ in (3) to (4), we have

$$\begin{aligned} 0 \preceq \mathbf{r}_d \preceq\ & \left[\min\left\{R_D^{S_{\rm ud}}(1 - \theta_{\rm du}), \beta_D R_R^{S_{\rm du}} \theta_{\rm du}\right\},\right. \\ & \left.\min\left\{R_R^{S_{\rm du}} \theta_{\rm du}, \beta_R R_R^{S_{\rm ud}}(1 - \theta_{\rm du})\right\}\right]^T. \end{aligned} \tag{5}$$

In each min function in the right hand side, there are two elements thus there are totally 4 cases to consider. Denoting

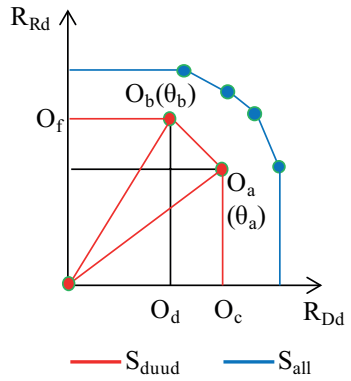


Fig. 4. Demonstration of the rate region of S_{duud}.

$m_1 = \beta_D \frac{R_D^{S_{\mathrm{du}}}}{R_D^{S_{\mathrm{ud}}}}$ and $m_2 = \beta_R \frac{R_R^{S_{\mathrm{ud}}}}{R_R^{S_{\mathrm{du}}}}$, we have.

- The first case is when $R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}) \le \beta_D R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}$ and $R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}} \le \beta_R R_R^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}})$. This is equivalent to $\frac{1}{m_1+1} \le \theta_{\mathrm{du}} \le \frac{m_2}{m_2+1}$. The rate region is now determined by $0 \preceq \mathbf{r}_d \preceq \left[R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}), R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}\right]^T$. If
$$\frac{1}{m_1+1} \le \frac{m_2}{m_2+1}, \tag{6}$$
the diagonal upper bound of this rate region part is a line segment with equation $R_{Dd} = R_D^{S_{\mathrm{ud}}} - \frac{R_D^{S_{\mathrm{ud}}}}{R_R^{S_{\mathrm{du}}}} R_{Rd}$ with two ends determined by $\theta_a = \frac{1}{m_1+1}$ and $\theta_b = \frac{m_2}{m_2+1}$ as seen in Fig. 4. If (6) is not satisfied, there is not any valid value of θ_{du}.
- The second case is when $R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}) > \beta_D R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}$ and $R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}} \le \beta_R R_R^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}})$. This is equivalent to $0 \le \theta_{\mathrm{du}} < \theta_a$ and the rate region is now determined by $0 \preceq \mathbf{r}_d \preceq \left[\beta_D R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}, R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}\right]^T$. Both R_{Dd} and R_{Rd} increases with θ_{du} and the line segment OO_a is determined.
- The third case is when $R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}) \le \beta_D R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}$ and $R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}} > \beta_R R_R^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}})$. This is equivalent to $\theta_b < \theta_{\mathrm{du}} \le 1$ and the rate region is now determined by $0 \preceq \mathbf{r}_d \preceq \left[R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}), \beta_R R_R^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}})\right]^T$. Both R_{Dd} and R_{Rd} decreases with θ_{du} and the line segment OO_b is determined.
- The forth case is when $R_D^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}}) > \beta_D R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}}$ and $R_R^{S_{\mathrm{du}}}\theta_{\mathrm{du}} > \beta_R R_R^{S_{\mathrm{ud}}}(1-\theta_{\mathrm{du}})$. This is equivalent to $\frac{m_2}{m_2+1} < \theta_{\mathrm{du}} < \frac{1}{m_1+1}$. If (6) is not satisfied, the diagonal upper bound of this rate region part is a line segment similar to case 1. If (6) is satisfied, there is not any valid value of θ_{du}.

If (6) is satisfied, the first three cases determine a triangle in which if we decrease R_{Rd} of point O_a correspondingly, we get the segment $O_a R_{Dd,1}$ and if we decrease R_{Dd} of point O_b correspondingly, we get the segment $O_b R_{Rd,2}$. The convex rate region is therefore formed as in Fig. 4. If (6) is not satisfied, the last three cases form a similar rate region.

The rate region of scheme S_{all} can be found by the algorithm described through the Pseudocode 1 in which k is the index vector of the outer points of all achievable rate pairs (x, y).

Pseudocode 1 Rate region for S_{all} (given $\mathbf{A}$, $\Delta\theta$)

```
i = 1;
for θ_du = 0 : Δθ : 1
    for θ_ud = 0 : Δθ : 1 − θ_du
        for θ_dd = 0 : Δθ : 1 − θ_du − θ_du
        ...
            for θ_uo = 0 : Δθ : 1 − θ_du − θ_du... − θ_do
                θ_TWR = 1 − −θ_du − θ_du... − θ_do − θ_uo
                r = Aθ
                x(i) = min(r(1), β_D r(2));
                y(i) = min(r(3), β_R r(4)); i = i + 1;
            end
            ...
        end
    end
end
k = convhull(x, y);
```

V. Multiple-User Scheduling

Considering a pair of one direct user and one relayed user with four traffic types (Dd, Du, Rd and Ru), we have collapsed the four-dimensional rate region to two-dimensional rate region by introducing UDCs. A natural question is what are the multiple-user schedulers that need to be used? In the following we describe how three commonly used schedulers can be adapted to the scheduling task defined in this paper: Round Robin with Equal Rates (RR ER) (Opportunistic Scheduler), Maximum Sum-Rate (MSR) and Proportional Fairness (PF).

We will make an additional distinction among the multi-user schemes. The composite schemes S_{all}, S_{CDR}, S_{ref} will be termed multi-user-epoch (MUE) schemes since two users are served in each epoch. As a reference, we consider single-user-epoch (SUE) schemes, in which a single user is served in an epoch. Thus, SUE is a composite scheme which in a given epoch can be either multiplexing of $S_{\mathrm{od}}, S_{\mathrm{ou}}$ (if the user is direct) or $S_{\mathrm{do}}, S_{\mathrm{uo}}, S_{\mathrm{TWR}}$, if the user is relayed.

A. Round Robin with Equal Rates

In order to emulate the original concept of round robin, here the two users (direct, relayed) are selected not based on the channel gains or achievable rates, but arbitrarily (e.g. by user ID). Without losing generality, we can say that in the first epoch the scheduler picks the first direct user and the first relayed user to make a pair and apply the composite CDR scheme. However, differently from a single–user scheduling schemes, here we have additional degrees of freedom also after the users are selected. These degrees of freedom are instantiated by changing the time–sharing vector $\boldsymbol{\theta}$. In order to further restrict the rate region, one possibility is to select $\boldsymbol{\theta}$ such that the downlink rates of the direct and the relayed user are equal. Recall that the uplink/downlink rates are related via UDC, such that the uplink rates of these users will have a ratio of $\beta_D : \beta_R$. In the next epoch, that user pair is put aside and the second direct user and the second relayed user are selected. If there are n_D direct users and n_R relayed users, the number of such epochs is $\min(n_D,\ n_R)$. After that the scheduler picks the next direct user (if $n_D > n_R$) or the next relayed user (if $n_R > n_D$) to serve as a single user in the next epoch, using an appropriate SUE. However, in order to make a fair time allocation, this single-user epoch is half-length of the

two-user epoch described before. In order words, two direct users or two relayed users are put into a two-user epoch strictly divided by 2. Consequently, the number of two-user epochs in a scenario is $\lceil \frac{k}{2} \rceil$, in which $\lceil x \rceil$ is the nearest integer $\geq x$, regardless of how many direct users and relayed users there are.

For a certain user pair and considering the UDCs, we have the conditions $R_{Dd} = R_{Rd}$, $R_{Dd} = \beta_D R_{Du}$ and $R_{Rd} = \beta_R R_{Ru}$. In other words, we have to select $\boldsymbol{\theta}$ so that the scheme $S_m,\ m \in \{\text{all}, \text{CDR}, \text{ref}, ...\}$ can provide the rates for Dd, Du, Rd and Ru with ratio $1 : \frac{1}{\beta_D} : 1 : \frac{1}{\beta_R}$. Considering the direct user and reasoning as in part IV-B, we select $R_{Dd} = \min\left\{\mathbf{a}_1^T\boldsymbol{\theta}, \beta_D\mathbf{a}_2^T\boldsymbol{\theta}\right\}$ and $R_{Rd} = \min\left\{\mathbf{a}_3^T\boldsymbol{\theta}, \beta_R\mathbf{a}_4^T\boldsymbol{\theta}\right\}$. Since $R_{Dd} = R_{Rd}$, we select the maximum among different $\boldsymbol{\theta}$ as in (7) in which $R_{(i,j)p}^{S_m}$ and $\mathbf{a}_{(i,j)q}^T$ are the rate of traffic type $p,\ p \in \{Dd, Du, Rd, Ru\}$ and the q-th row of the matrix $\mathbf{A}$ corresponding to the user pair (i,j) offered by scheme S_m respectively and $\boldsymbol{\theta}_m$ is the time segment ratio vector corresponding to scheme S_m, e.g. S_{CDR} has a vector of $\boldsymbol{\theta}_{\text{CDR}} = [\theta_{\text{du}}\ \theta_{\text{ud}}\ \theta_{\text{dd}}\ \theta_{\text{uu}}\ 0\ 0\ 0\ 0\ 0]^T$. This problem is to find an optimal vector $\boldsymbol{\theta}_m$ which gives the highest downlink rates for a selected user pair. The procedure continues until all users are served as described above. After all user pairs are served, either only direct or relayed users are left, which are served through SUE. The average downlink rate offered by CDR with RR ER can be worse than that of SUE with RR ER, since the equal rate constraint limits the rate of the stronger user. This will be examined and discussed in the section with Numerical Results.

B. Maximum Sum-Rate

The Maximum Sum-Rate scheduler always selects the pair with the highest sum-rate to serve considering UDCs. The achievable downlink rate of direct user i is $\min\left(\mathbf{a}_{(i,j)1}^T\boldsymbol{\theta},\ \beta_D\mathbf{a}_{(i,j)2}^T\boldsymbol{\theta}\right)$ and the achievable downlink rate of a relayed user is $\min\left(\mathbf{a}_{(i,j)3}^T\boldsymbol{\theta},\ \beta_R\mathbf{a}_{(i,j)4}^T\boldsymbol{\theta}\right)$. Therefore the user pair selected in an epoch favors the users with good channels and is described as in (8).

C. Proportional Fairness

In this part we use Proportional Fairness (PF) [18], [22]–[24] as a metric for selecting a user pair in an epoch. In an epoch, PF selects the user with the highest ratio of its instantaneous rate and its average rate to serve. In the following, we consider UDC with PF which is long-term. This is viable because PF is actually related to the competition of flows from different users, while the UDC requirements capture the relation between the flows belonging to the same user.

The average rate of user i at the beginning of session $t+1$ if during epoch t, user i is provided a rate of $R_i(t)$ is $\bar{R}_i(t+1) = 0$ if $t = 0$ and $\bar{R}_i(t+1) = \frac{n_e-1}{n_e}\bar{R}_i(t) + \frac{1}{n_e}R_i(t)$ if $t > 0$. Here, by user rate, we refer to his downlink rate and n_e is the number of epochs. Its uplink rate is scaled down by a corresponding ratio β_D or β_R due to UDCs.

Normally, in a PF scheduler, at a certain time, only one user, which has the highest PF, is selected. However, there are some proposals for a scenario in which several users can be selected at the same time since there are several available resource portions such as in OFDM system where there are several sub-carriers which can be assigned to different users at the same time. Among those, [23] proved that a scheduler is proportionally fair for a multi-carrier transmission system if and only if it satisfies

$$P = \arg\max_S \prod_{i \in U}\left(1 + \frac{R_i(t)}{(n_e - 1)\bar{R}_i(t-1)}\right) \tag{9}$$

in which S is any scheduler, U is the considered user set, $R_i(t)$ is the total rate provided to user i at session t, and $\bar{R}_i(t-1)$ is the average of user i after the previous session.

In our case, we have to select two users in an epoch, therefore we can treat our scenario as an OFDM system with two sub-carriers. Thus the product in (9) has only two factors. The downlink rate provided by a composite scheme to a user can be seen as the rate a user can achieve when using a certain sub-carrier. The difference is that we cannot select two direct users or two relayed users and the resources are not fixed as the sub-carriers in OFDM but optimized using another degree of freedom.

Here in each epoch we select two users thus when we consider a user pair, the current rates of other users are 0. In a session, the achievable downlink rates of a direct user and a relayed user in the user pair (i,j) are $\min\left(\mathbf{a}_1^T\boldsymbol{\theta},\ \beta_D\mathbf{a}_2^T\boldsymbol{\theta}\right)$ and $\min\left(\mathbf{a}_3^T\boldsymbol{\theta},\ \beta_R\mathbf{a}_4^T\boldsymbol{\theta}\right)$ respectively. Therefore the user pair selected in an epoch according to PF is given in (10).

VI. Numerical Results

A. Two-User Scenario

In this section we calculate the rate region for a two-user scenario with fixed channels. Fig. 5 shows the downlink rate regions (R_{Dd}, R_{Rd}) of different combined schemes S_{all} (all schemes), S_{ref} (all conventional schemes), S_{duud} (CDR schemes 1 and 2), S_{dduu} (CDR schemes 3 and 4) and S_{CDR} (all CDR schemes) in case of channels $\bar{\gamma} = [\gamma_{BL}\ \gamma_{LR}\ \gamma_{BD}\ \gamma_{RD}\ \gamma_{LD}\ ] = [10\ 10\ 10\ -10\ 10]$dB and $\beta_R = \beta_D = 4$. To calculate the rate region, the values of $\theta_i,\ i \in \{\text{du}, ..., \text{TWR}\}$ use resolution $\Delta\theta_i = 0.08$. The rate region of S_{all} certainly contains all of the other rate regions because it is the general case consisting of all value of $\theta_i,\ i \in \{\text{du}, ..., \text{TWR}\}$.

The rate region of S_{CDR} is larger than the union of the rate regions of S_{duud} and S_{dduu} while the rate region S_{all} is also larger than the union of the rate regions of S_{CDR} and S_{ref}. This is because θ_m has to be selected such that UDCs are satisfied. S_{CDR} provides almost equal rates for the direct and relayed users while S_{ref} provide a low rate for the relayed user by prioritizing the direct user. This is because the CDR schemes feature joint transmissions which contribute to the rates of both users.

B. Multiple-User Scenario

In this section we calculate the average downlink rate and the PF coefficient for users with randomized positions in a network. In the simulation, we run $n_{\text{iteration}} = 1000$ scenarios. In a scenario, $k = 20$ users are randomly put in a circular cell with uniform distribution. The cell has a normalized radius

$$\begin{aligned}(i_o, j_o) &= \arg\max_{\boldsymbol{\theta}} \min\left\{R^{S_m}_{(i,j)Dd}(\boldsymbol{\theta}),\ \beta_D R^{S_m}_{(i,j)Du}(\boldsymbol{\theta}),\ R^{S_m}_{(i,j)Rd}(\boldsymbol{\theta}),\ \beta_R R^{S_m}_{(i,j)Ru}(\boldsymbol{\theta})\right\} \\ &= \arg\max_{\boldsymbol{\theta}} \min\left\{\mathbf{a}^T_{(i,j)1}\boldsymbol{\theta}_m,\ \beta_D \mathbf{a}^T_{(i,j)2}\boldsymbol{\theta}_m,\ \mathbf{a}^T_{(i,j)3}\boldsymbol{\theta}_m,\ \beta_R \mathbf{a}^T_{(i,j)4}\boldsymbol{\theta}_m\right\}\end{aligned} \tag{7}$$

$$(i_o, j_o) = \arg\max_{i,j\in U} \max_{\boldsymbol{\theta}} \left(\min\left(\mathbf{a}^T_{(i,j)1}\boldsymbol{\theta},\ \beta_D \mathbf{a}^T_{(i,j)2}\boldsymbol{\theta}\right) + \min\left(\mathbf{a}^T_{(i,j)3}\boldsymbol{\theta},\ \beta_R \mathbf{a}^T_{(i,j)4}\boldsymbol{\theta}\right)\right) \tag{8}$$

$$(i_o, j_o) = \max_{i,j\in U} \max_{\boldsymbol{\theta}} \left(1 + \frac{\min\left(\mathbf{a}^T_{(i,j)1}\boldsymbol{\theta},\ \beta_D \mathbf{a}^T_{(i,j)2}\boldsymbol{\theta}\right)}{(n_e - 1)\bar{R}_i(t-1)}\right)\left(1 + \frac{\min\left(\mathbf{a}^T_{(i,j)3}\boldsymbol{\theta},\ \beta_R \mathbf{a}^T_{(i,j)4}\boldsymbol{\theta}\right)}{(n_e - 1)\bar{R}_j(t-1)}\right) \tag{10}$$

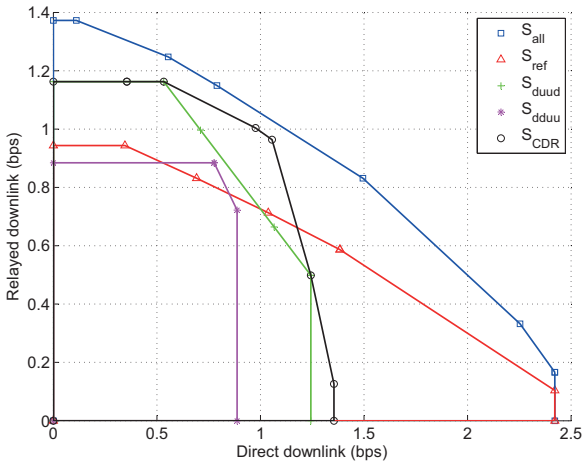


Fig. 5. Simulation results of rate regions of S_{all}, S_{ref}, S_{duud}, S_{dduu} and S_{CDR} with $\bar{\gamma} = [\gamma_{BL}\ \gamma_{LR}\ \gamma_{BD}\ \gamma_{RD}\ \gamma_{LD}\ ] = [10\ 10\ 10\ -10\ 10]$dB and $\beta_R = \beta_D = 4$.

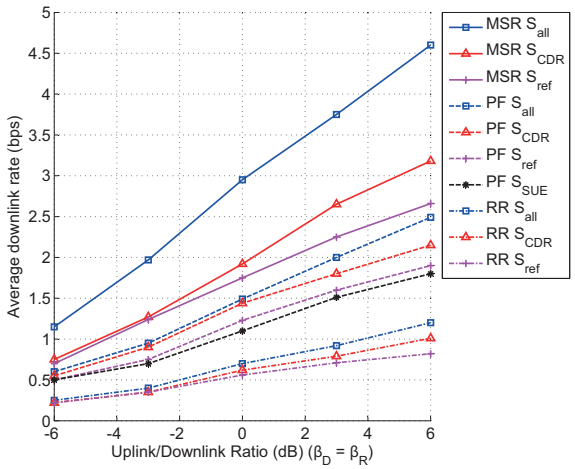


Fig. 6. Average downlink rate of some composite schemes with different uplink/downlink coefficients when different schedulers are used.

of $R = 1$. The BS is at the center of the cell which is also the origin of the coordinate system $O(0, 0)$. 4 relay stations are placed at the angle $\phi = 0,\ \frac{\pi}{2},\ \pi,\ \frac{3\pi}{2}$ respectively and away from the BS with a normalized distance of $R_r = 0.7$. A user is determined to be a direct user if it is inside the circle with center at O and radius of $R_r = 0.7$ as a similar principle in [21]. Any other user is determined as relayed user, attached to the nearest relay station. The number of direct users n_D and the number of relayed users $n_R = k - n_D$ are not necessarily equal. All channels are modeled as $h = \frac{h_f}{\sqrt{d^{p_l}}}$ in which h_f is a Rayleigh fading coefficient with variance $\sigma_f = 1$, d is the distance between the transmitter and the receiver and path loss coefficient $p_l = 3$. We compare the performance of the composite MUE schemes $S_m,\ m \in \{\text{all}, \text{CDR}, \text{ref}\}$ and composite SUE considering different schedulers RR ER, MSR and PF.

In a scenario, there are $n_e = 200$ epochs. In an epoch with RR ER scheduler, a user pair or a single user is served. After that a new pair or user is selected until no user is left. If a user pair is selected, the linear optimization problem presented in V-A is solved to find the optimal $\boldsymbol{\theta}_m$. The rates will be calculated accordingly based on the formulas in sections III, V. If a single user is selected, since all channels are reciprocal and therefore the maximal downlink rate and maximal uplink rate are the same for both users, the single-user epoch is divided into two parts with ratio $\beta_i : 1,\ i \in \{D, R\}$. In an epoch with MSR scheduler, the user pair which has the highest total downlink rate provided by S_m is selected.

In an epoch with with PF scheduler, a time fraction vector which can maximize the PF coefficient as defined in (10) using a composite scheme S_m is determined for each relayed-direct user pair. The pair with the highest maximum PF coefficient is selected. In case of SUE, the user with the highest maximum PF coefficient is selected as $i_o = \arg\max_{i\in U} \frac{r_i}{\bar{R}_i}$ in which U is the user set, $r_i,\ \bar{R}_i$ are the provided rate and average rate of user i in an epoch.

The average downlink rate of all users when different composite schemes and different schedulers are used is shown in Fig. 6. In this simulation, all downlink rates of all users are summed up and divided by the total time used by all users in a given scenario. For each of schedulers RR ER, MSR and PF, the order from the best to the worst is S_{all}, S_{CDR}, S_{ref} and SUE. SUE performs worse than S_{ref} does since it lacks S_{TWR}. As expected, the MSR scheduler has the highest sum rate, while the PF scheduler is better than the RR ER scheduler because it tries to maximize the network rate taking into account the PF coefficient.

Fig. 7 shows the results of PF coefficients of the schemes and we can see that the comparison is similar to the results of the average user's downlink rate. The results for MSR scheduler are not shown, but MSR performs poorest in terms

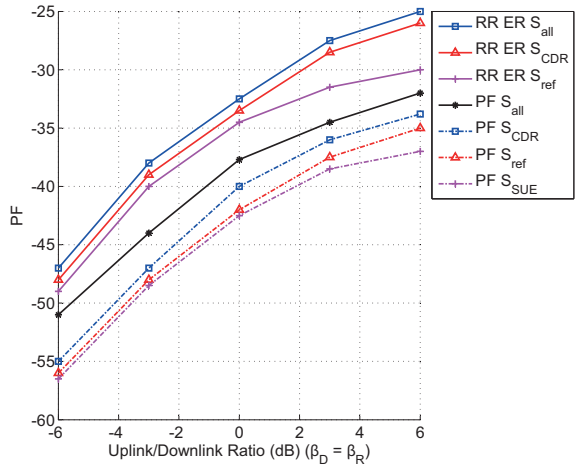


Fig. 7. PF of $S_{\rm all}$, $S_{\rm CDR}$, $S_{\rm ref}$ and SUE with different uplink/downlink coefficients and MSR and PF schedulers.

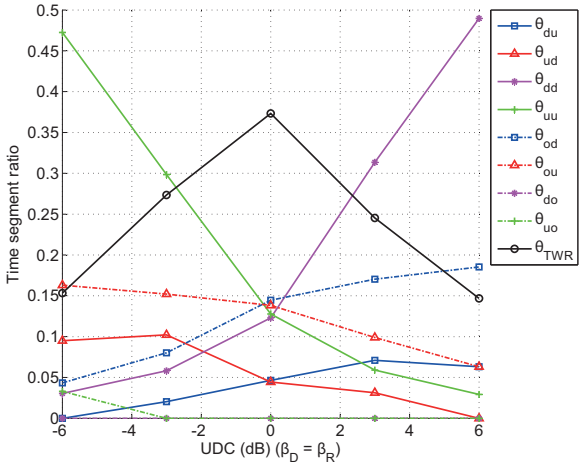


Fig. 8. Time fractions of the individual schemes in $S_{\rm all}$ with different uplink/downlink coefficients and PF scheduler.

of fairness. In Fig. 8, we can see the time fraction pairs ($\theta_{\rm du}$, $\theta_{\rm ud}$), ($\theta_{\rm dd}$, $\theta_{\rm uu}$), ($\theta_{\rm od}$, $\theta_{\rm ou}$), ($\theta_{\rm do}$, $\theta_{\rm uo}$) and $\theta_{\rm TWR}$ which are almost symmetric with the axe of symmetry $\beta = 0$ dB. This is because in each pair, the time fractions provide opposite traffic types and the single fraction $\theta_{\rm TWR}$ provides a symmetric traffic type.

The results point out that in a certain scenario, no individual scheme is consistently better than the others, seen in non-zero time fractions allocated to the other schemes. Although the general composite scheme is the best, the results point out that if we have to select a simpler composite scheme, comprising a lower number of individual schemes, then the CDR schemes are preferable because they not only improve the rates but also the fairness compared to the state-of-the-art conventional schemes. This is valid for all schedulers. Moreover, the result show that with CDR schemes, it is still correct that MSR gives the highest rate and RR ER gives the lowest rate among the considered schedulers. Especially the application of the PF scheduler along with the CDR schemes supports rate pairs that exhibit fairness and are not attainable by the reference

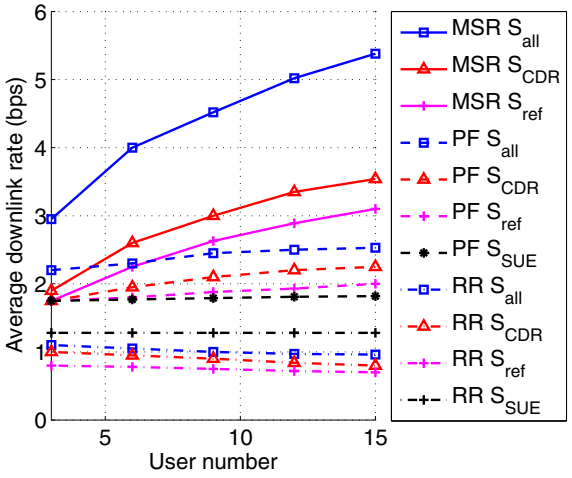


Fig. 9. Average downlink rate versus user number.

state-of-the-art schemes.

When the user number increases (Fig. 9), the downlink rate of both MSR and PF scheduler increases since the multiuser diversity gain increases. Composite CDR schemes with RR ER scheduler are actually worse than SUE with RR ER, since they have to deliver equal rates to the two users in a pair. This limits the rates of both users quite a lot, while in SUE with RR RE the rates are delivered to the individual users by time multiplexing. Furthermore, the downlink rate of composite CDR scheme with RR ER slightly decreases with the user number due to the following reason. According to part V-A, after all users pairs are served, the direct or relayed users left are served user by user using SUE. A multi-user composite CDR scheme has two phases: serving user pairs and single users. Because CDR with RR ER is worse than SUE with RR ER, the average rate of the first phase is lower than that of the second phase. In addition, the average ratio $\frac{n_2}{k}$, where n_2 is the number of the users served in the second phase, decreases with k thus the performance of CDR schemes with RR ER decreases with k.

The results show that the comparison among the schemes and schedulers does not change with different number of users. Depending on which scheduler is used, a certain number of users can be considered as appropriate and selected. Increasing the number of users does not always increase the average rate.

VII. Conclusion

In this paper we have investigated different multi-flow transmission (MFT) schemes in a wireless cellular scenario with combined direct/relay users. An example of a MFT scheme is two-way relaying and each MFT scheme can be used as a building block of more complex transmission schemes for serving multiple users. We have introduced a framework based on time-multiplexed composite transmission scheme that is able to integrate various MFT schemes, as well as the conventional single-flow transmission schemes. We have illustrated how this framework can be utilized to analyze the rate regions of scenarios in which multiple users have two-way traffic. The analysis is made by adapting well-known scheduling policies (Round Robin, Max Rate, and

Proportional Fair) to the proposed framework. Future work includes identification of other scenarios that can benefit from the MFT schemes, as well as considerations of MFT schemes with relaying methods that are more advanced compared to the amplify-and-forward.

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